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ABSTRACT

This work was performed under a task entitled "Development and Assessment of ADL Prototypes." This task is intended to promote collaboration by the Services and by other government and academic partners in developing technology-based instruction. It is an essential component of the Advanced Distributed Learning (ADL) initiative being undertaken by the Department of Defense (DoD) in cooperation and coordination with the Office of Science and Technology Policy (OSTP). This particular document is intended to provide an overview of technology-based instruction. Writing and printed books have influenced learning profoundly. It seems reasonable to view the emergence of writing as the first major revolution in learning. By making the content of learning, teaching, and educational material widely and inexpensively available anytime and anywhere, the development of books printed from movable type effected a second revolution in learning. Can we improve on books? Computer technology is a possibility because computers can adapt the content, sequence, type, difficulty, granularity, and so forth of their presentations to learners or problem solvers based on ongoing, dynamic assessments of individual needs. For this reason, computer technology may be effecting a third revolution in learning. While preserving the capabilities of books to present the content of instruction anytime, anywhere, computers can also provide the interactions of teachers, instructors, tutors, and mentors as needed by individual learners and users. This capability may produce a third revolution in learning, with a significance equal to that of the development of writing and books. This document addresses this "Third Revolution" in learning by assessing the impact of computer-based technology on learning. Consequences of this third revolution include making individualized tutoring widely accessible and affordable; permitting interactive, individualized learning to take place anytime, anywhere; changing the way that educational institutions and educators view learning by producing radical changes in the practice and processes of instruction; and bringing into being a nation of life-long learners who are prepared to meet future technological challenges and thrive in the global marketplace. Includes a glossary of abbreviations. (Contains 43 references.) (Author)

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J. D. Fletcher

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Technology, the Columbus Effect, and the Third Revolution in Learning

J. D. Fletcher

PREFACE

This work was performed under a task entitled "Development and Assessment of ADL Prototypes." This task is intended to promote collaboration by the Services and by other government and academic partners in developing technology-based instruction. It is an essential component of the Advanced Distributed Learning (ADL) initiative being undertaken by the Department of Defense (DoD) in cooperation and coordination with the Office of Science and Technology Policy (OSTP). This particular document is intended to provide an overview of technology-based instruction.

CONTENTS

EXECUTIVE SUMMARY **ES-1**

TECHNOLOGY, THE COLUMBUS EFFECT, AND THE THIRD REVOLUTION IN LEARNING **1**

A. Introduction 1
B. The Third Revolution in Learning 3
C. Does Interactivity Matter? 4
D. Tutoring and the Individualization of Instruction 4
E. Intensity or Interactivity of Instruction 6
F. Pace of Instruction 8
G. Cost Effectiveness 11
H. Intelligent Tutoring Systems 12
I. The Columbus Effect in Instructional Technology 14
J. Impact on Research and Theory 16
K. The Engineering of Instruction 17
L. Impact on our Curricular Goals 18
M. Summary 19

References Ref-1

Glossary GL-1

EXECUTIVE SUMMARY

Writing and printed books have influenced learning profoundly. The emergence of writing brought about a revolution in learning by freeing learners from requirements for face-to-face interaction with sages and other human sources of knowledge, lore, and information. Although learning became neither inexpensive nor universally available after the development of written language, its content became available anytime, anywhere.

A second revolution occurred with the development of moveable type and books. These developments also made the content of learning, teaching, and educational materials available anytime, anywhere—but more widely and, significantly, less expensively.

Can we improve on books? Computer technology arises as a possibility. Computers can adapt the sequence and type of operations they perform to the conditions of the moment. In instruction, they can adapt the content, sequence, type, difficulty, granularity, and so forth of their presentations to learners or problem solvers based on ongoing, dynamic assessments of their individual needs.

For this reason, computer technology may be effecting a third revolution in learning. While preserving the capabilities of books to present the content of instruction anytime, anywhere, computers can also provide the interactions of teachers, instructors, tutors, and mentors as needed by individual learners and users. This is not something books, movies, television, or videotape technologies can do affordably or to any significant degree. By presenting the content and the interactions of instruction, computers promise a new and significant capability for learning that is available anytime, anywhere. This capability may produce a third revolution in learning, with a significance equal to that of the development of writing and books.

Some findings that suggest this revolution is likely and within reach are:

- **Individualization.** Experimental studies comparing human tutors using only rudimentary techniques of individualization with classroom instruction have found effect sizes as large as 2.00 standard deviations favoring the tutored students. Technology makes such tutoring capabilities affordable.
- **Adaptation and interactivity.** As a form of individualization, branched instruction that adjusts its content and pace for individual learners has been

compared with a strictly linear presentation of the same instructional material using identical delivery devices. Studies found effect sizes of 0.72 and 2.16 standard deviations favoring the branched approaches and indicate the value of adaptation and interactivity in instruction.

- **Intensity of instruction.** An individual student in classroom instruction is required to answer an average of about 0.11 questions an hour. In tutored instruction, the number of questions an individual student is required to answer has been found to range from 117 to 146 questions an hour. Results from some technology-based instruction have been found to average about 120 questions during 12-minute sessions. The intensity of individual tutoring and technology-based instruction far exceeds that of classroom instruction.
- **Pace of instruction.** The ratio of time the fastest students in a typical classroom need to achieve mastery of material being presented compared with the time needed by the slowest students is about 1:5. This spread of capabilities is very difficult for human classroom teachers to satisfy, despite their heroic efforts to do so. Some students will inevitably be bored, and others will be lost. Many studies have found that allowing students to use technology-based instruction to progress at their own rates and receive material tailored to their own needs reduces overall time-to-mastery by about 30 percent.
- **Cost-effectiveness.** When compared with reduced class size, increased instructional time, peer tutoring, and professional tutoring, technology–based instruction was found to be the most cost-effective approach among these alternatives.
- **Intelligent tutoring systems.** Intelligent tutoring systems intended to replicate the practices of expert human tutors have demonstrated effect sizes of 0.84 to 1.00 standard deviations when compared with classroom instruction. These systems appear to have raised significantly the ceiling for instructional improvements potentially available from technology-based instruction. They may end up using approaches that are different and far more powerful than those used by human tutors. Through the use of web-accessed instructional objects and personal (perhaps wearable) learning associates, these systems may yield unexpected and unanticipated results.

It seems reasonable to conclude that this third revolution will:

- Make the functionalities of individualized tutoring widely accessible and affordable
- Permit interactive, individualized learning to take place anytime, anywhere
- Eventually bring about profound changes in our educational institutions and in the roles and responsibilities of the people (instructors, students, and administrators) who work in them

- Help bring into being a nation of life-long learners who are well prepared to meet the challenges of technological change and thrive in the global market-place
- Produce radical change in the practice and processes of instruction
- Change what we do and what we aspire to do in instruction.

TECHNOLOGY, THE COLUMBUS EFFECT, AND THE THIRD REVOLUTION IN LEARNING

A. INTRODUCTION

The apocryphal tale goes something like this:

> An Enlightened Leadership discovers that relatively minor investments in educational technology can significantly enhance the capabilities—the productivity, competitiveness, and competence—of their domain. The next step, of course, is to appoint a "Blue-Ribbon" Committee. The task of the Committee is to design the ideal technology for education. The Committee meets, deliberates, and issues specifications for the new technology.
>
> Physically, it must be rugged, lightweight, and easily portable—available anytime, anywhere. It must operate indoors and out, under a wide range of temperature, humidity, and other environmental conditions, and it must require only minimal, if any, external power support. Functionally, it must provide easy, rapid, and random access to high-quality text, black and white or full-color graphics, and high-resolution photographs. It must include an interface that is easily understood and usable by all, preferably communicated in natural language. It should allow self-pacing (i.e., learners should be able to proceed through instructional content as rapidly or as slowly as needed). It should be suitable for life-long learning and readily available to a wide range of users in home, school, and workplace settings. Economically, it must be inexpensive, or as the Committee reports "require only minimal financial investment on the part of potential end users."
>
> The Enlightened Leadership receives the Committee's report with relief. Development of the technology will require no lengthy research and development, no new taxes, no new infrastructure, and no difficult political or administrative decisions or compromises. In fact, the only thing it will require is business as usual. The reason may be as obvious to the readers as it is to the Enlightened Leadership. The recommended technology is, of course, the technology of books—which are already available and in place.

Writing and books effected revolutions in learning or, more precisely, how we go about the business of learning. Before their appearance, during the earlier 100,000 or so years of human (i.e., homo sapiens) existence, instruction took place person to person. It was expensive and slow and produced uneven results because it depended heavily on the teacher's knowledge, capabilities, and instructional expertise. Matters concerning more than basic subsistence reached very few people.

Writing developed about 7,000 years ago and progressed from picture-based ideographs to consonants and vowels represented with alphabet-based phoneticization by perhaps 1000 BC. It allowed the content of advanced ideas and teaching to transcend time and place. Because of that capability, it effected a major revolution in learning. People with enough time and resources could study the words of the sages who went before them without having to rely on face-to-face interaction or the vagaries of human memory.

As discussed by Kilgour (1998), books (i.e., something beyond mud or stone tablets) were copied first on papyrus and later on parchment rolls until about 300 BC when the Romans began to sew sheets of parchment together into codices. These codices resembled the books of today and allowed easier and random access to the content. They were also less costly to produce than papyrus rolls because they were based on locally available parchment made from animal skin and allowed content to be placed on both sides of the sheets. Use of paper prepared from linen and cotton [about 100 AD (China) and 1200 AD (Europe)] made books even less expensive. Still, books were by no means inexpensive. However, their lowered costs made them more available to a literate and growing middle class who increased the demand for books and the learning they provided. This increased demand, in turn, lowered costs even further.

The full technology called for by the Committee mentioned previously finally became available with the introduction of books printed from moveable type (Kilgour, 1998). These printed books were first produced in China around 1000 AD and in Europe in the mid 1400s. At this point, the content of knowledge and teaching became widely and increasingly inexpensively available. The only item lacking from the Committee's list of specifications was the availability of high-resolution photographs, which had to await the development of photography in the mid 1800s.

Writing and printed books have impacted learning profoundly. It seems reasonable to view the emergence of writing as (among other things) the first major revolution in learning. Although learning—the acquisition of knowledge—was still neither inexpensive nor widely available, it no longer required face-to-face interaction with sages. By making the content of learning, teaching, and educational material widely and inexpensively available anytime and anywhere, the development of books printed from moveable type effected a second revolution in learning.

THE THIRD REVOLUTION IN LEARNING

At this point, we might consider an argument often advanced but best articulated by Clark (1983). In discussing all the means (media) we have for delivering instruction, Clark asserted, "the best current evidence is that media are mere vehicles that deliver instruction but do not influence student achievement any more than the truck that delivers our groceries causes changes in our nutrition" (p. 445). Of course, Clark had in mind more recently developed media than books, but printed books seem fair game for discussion in this context.

Are books "mere vehicles" for delivering instruction? Do they deserve more credit than that for influencing student achievement? Just as trucks are essential components in an infrastructure that has improved the nutrition of nations, books are essential components in an infrastructure that has improved the learning, performance, and competence of people everywhere. Both trucks and books may be vehicles, but their contributions seem to be more fundamental than "mere."

However, the heart of Clark's argument remains sound. Books do not guarantee learning or student achievement. Ignorance remains plentiful, even though books have diminished its supply appreciably. Clark's concern can be summed up by the notion that technology alone does not define an instructional approach. What matters is what is done with the technology. This point of view seems fair and unequivocal. The presence of any technology does not guarantee that effective instructional content, effective ways to present this content, or even the unique strengths of the technology itself will be present or used. On the other hand, the absence of a technology is a reasonable guarantee that its functionalities will be missing. Without printed books, we may be back to the 1400s.

How do we improve on books? Do we have anything better? Computer technology arises as a possibility. One of the most important statements in higher order computer languages (based necessarily on what is available in every digital computer's lower-order instruction set), is the "if" statement. This statement is of the (very) general form:

If <some condition> is true, then do <something>; otherwise, do <something else>.

We can marvel at the capabilities of computers to perform millions of operations a second with perfect accuracy on the immense amounts of data that they retrieve. However, the central point for this discussion is the capability of computers to adapt the sequence and the type of operations they perform based on conditions of the moment. More specifically, they can adapt the content, sequence, type, difficulty, granularity, and so forth of

resentations to learners and other users based on their assessment of learners' and users' current needs.

For this reason, computer technology may effect a third revolution in learning. While preserving the capabilities of writing and books to present the content of excellent instruction anytime, anywhere, computers can also provide the interactions of excellent teachers, instructors, tutors, and mentors as needed by individual learners. This is not something books, movies, television, or videotape technologies can do affordably or to any appreciable degree. This interactivity is a new and significant capability. It is the core of what future commentators may view as the third revolution in learning.

C. DOES INTERACTIVITY MATTER?

Much of the remainder of this discussion centers on whether the instructional interactivity provided by technology matters. Can we expect a revolution in instruction equivalent to that wrought by writing and books? What can we say about the nature of this revolution and what it implies for instructional practice?

The question of whether interactivity matters is addressed to some degree by studies in which as much of the instruction as possible is held constant except for the level of interactivity. Fowler (1980) and Verano (1987) performed two such studies. Fowler compared branched presentations using computer-controlled, adaptive videodisc instruction with instruction in which the same materials were held to a fixed-content, linear sequence. She reported an effect size of 0.72 (roughly, an improvement from the 50th to the 76th percentile in performance) for ability to operate and locate faults on a movie projector, which was the object of her instruction. Similarly, Verano also compared an interactive, adaptive, branching approach for presenting instructional material with a strictly linear approach used to present identical instruction in beginning Spanish. Both of his treatments used videodisc presentations. He reported an effect size of 2.16 (roughly, an improvement from the 50th to the 98th percentile in performance) in end-of-course knowledge. These two studies, among others, suggest that interactivity—at least, interactivity as defined by these studies—matters and perhaps a great deal. Of course, there is more to the story.

D. TUTORING AND THE INDIVIDUALIZATION OF INSTRUCTION

Individualized tutoring (one student working with one instructor) has been viewed and used for a long time as an effective instructional procedure. Evidence of its value is found in its continued use for instruction in highly complex and high-value activities, such

s aircraft piloting, advanced scientific research, and specialized medical practice. Comparisons of one-on-one tutoring with one-on-many classroom instruction might be expected to favor individualized tutoring, and they do. However, these comparisons are surprising not because of the direction of these findings, but because of the magnitude of the differences in instructional effectiveness.

Benjamin Bloom's results may be the most widely noted of these. Combining the findings of three empirical studies that compared one-on-one tutoring with classroom instruction, Bloom (1984) reported a general difference in achievement of two standard deviations (roughly, an improvement from the 50th to the 98th percentile in performance) in favor of tutoring. On the basis of considerable empirical evidence, these and similar studies suggest that differences between the results of one-on-one tutoring and classroom instruction are not just likely but very large.

Why, then, do we not provide these manifest benefits to all our students? The answer is straightforward and obvious and has doubtless already occurred to the reader: we cannot afford it. The issue is not effectiveness, but cost. Unless our policies toward educational funding change dramatically, we cannot afford a single tutor for every student. Bloom (1984) popularized this issue as the Two-Sigma[1] Problem.

In 1975, Scriven argued that individualized instruction was an instructional imperative and an economic impossibility. Is it? Must instruction remain constrained by this reality?

Enter Moore's (famous) Law.[2] As recounted by Mann (2000), *Electronics* magazine interviewed Moore in 1965 and inquired about the future of the microchip industry. To make a point, Moore noted that engineers were doubling the number of electronic devices (basically transistors) on chips every year. In 1975, Moore revised his prediction to say that the doubling would occur every 2 years. If we split the difference and predict that it will occur every 18 months, our expectations fit reality quite closely. As Mann points out, the consequence of Moore's Law is that computers that initially sell for $3,000 will cost about half that in about 18 months.

Moore's Law has implications for our learning applications: Computers are becoming exponentially less expensive, and the computational capabilities that we need to

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1 As in two standard deviations.

2 Gordon Moore is a semiconductor pioneer and co-founder of Intel Corporation.

ıpport instruction that is very much like individualized tutoring are becoming progressively affordable—if they are not already. The issue then becomes this: How we should use this increasingly affordable computational power to support learning?

Since the 1960s (e.g., Suppes, 1964; Atkinson and Fletcher, 1972), we have had computer-based instruction (CBI) that could tailor the content, sequence, and difficulty of instructional content to the needs of individual learners, and these approaches were shown to be effective. The Stanford beginning reading programs presented on Model 33 teletype-writers running at 110 baud (about 10 characters per second) with randomly accessible digitized audio achieved effect sizes in excess of 0.80 standard deviations (Fletcher and Atkinson, 1972). Similar results were obtained for elementary school mathematics (Suppes, Fletcher, and Zanotti, 1975). Instructional approaches used in these early programs required computers that cost $2–3 million; however, today, computers that cost under $1,000 could easily present these same approaches.

These approaches did not seek to mimic directly the interactions that occur in human tutorial instruction. Instead, they attempted to apply results emerging from empirical studies of human cognition, memory, and learning as discussed by Suppes (1964) and Atkinson (1972). Efforts to provide tutorial dialogue emerged from approaches that were initially described as intelligent computer-assisted instruction (CAI) and later as intelligent tutoring systems (ITSs) (Sleeman and Brown, 1982; Woolf and Regian, 2000). They have been effective, occasionally yielding effect sizes in excess of 1.00 (e.g., Gott, Kane, and Lesgold, 1995). These approaches raise the following questions: What accounts for the success of one-on-one tutorials? Can we do the same with computers?

E. INTENSITY OR INTERACTIVITY OF INSTRUCTION

Graesser and Person (1994) discussed this issue. They compared instruction using one-on-one tutoring with classroom practice in two curriculum areas: research methods for college undergraduates and algebra for 7th graders. Tutors for the research methods course were psychology graduate students, and tutors for the algebra course were high school students.

Graesser and Person found the following:

- Average number of questions asked by teachers in a class in a classroom hour: 3
- Average number of questions asked by any one student during a classroom hour: 0.11

- Average number of questions asked by a student and answered by a tutor during a tutorial hour:
  - Research methods: 21.1
  - Algebra: 32.2
- Average number of questions asked by a tutor and answered by a student during a tutorial hour:
  - Research methods: 117.2
  - Algebra: 146.4.

These data do not prove hard-core cause and effect, but they show great differences in sheer interactivity between two approaches that also show great differences in instructional effectiveness.

Does CBI echo this level of interactivity? Few studies report the number of questions students answer per unit of time when using technology. However, this author (Fletcher) found that K–3 students who receive technology-based beginning-reading and beginning-arithmetic instruction on the previously mentioned 110-baud teletypewriters were answering 8–12 questions a minute—questions that were individually assigned and whose answers were immediately assessed.

This level of interactivity would extrapolate to 480–720 such questions an hour if children of this (or any) age were able to sustain this level of interaction for 60 minutes. Instead, these children generally worked with the computer-based materials in daily 12-minute sessions, which extrapolates to 96–144 individually selected and rapidly assessed questions that these children received each day. As mentioned previously, this CAI was producing effect sizes in excess of 0.80 standard deviations in comparisons with classroom instruction in mathematics and reading. The speed, or pace, with which students were allowed to progress through instructional presentations, as much as anything else, may be responsible for the success of these and other CAI programs.

Graesser, Person, and Magliano (1995) point out that the neither the students nor the tutors they observed were particularly sophisticated in their use of questions. Specifically, they found that the tutorial techniques long advanced by researchers and scholars[3] were largely absent. About half of the questions asked by the students and their tutors

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[3] For example, shaping and fading (Skinner, 1968), scaffolding (Ausubel, 1960; Rogoff, 1990), reciprocal instruction (Palincsar and Brown, 1984), error diagnosis and repair (Burton, 1982; van Lehn, 1990), or advanced motivational approaches (Lepper et al., 1993).

required simple yes/no responses. The techniques the tutors used were far from sophisticated, but these techniques, as the data tell us, were effective. Simple approaches that aim primarily to increase interactivity may by themselves fill much of Bloom's two-sigma gap.

However, greater sophistication in one-on-one tutoring also pays off. Semb et al. (2000) reviewed several empirical studies of on-the-job training (OJT) and concluded that greater knowledge and use of tutorial techniques result in greater achievement and more efficient learning. These applications are found primarily in the military and industrial world, but they are, effectively, one-on-one tutoring. Including advanced tutorial techniques in our computer-based tutors may allow us to exceed Bloom's two-sigma threshold. We may have just begun.

F. PACE OF INSTRUCTION

The possibility that simple approaches may, by themselves, do much to fill Bloom's two-sigma gap is supported by considerations of pace: the speed with which students learn material and reach instructional objectives. Easily adjusted pacing is a capability claimed by even the most rudimentary CBI systems.

Many teachers have been struck by the differences in the pace with which their students can learn. Consider, for instance, some findings on the time necessary for different students to reach the same instructional objectives:

- Ratio of time needed by individual kindergarten students to build words from letters: 13 to 1 (Suppes, 1964)
- Ratio of time needed by individual hearing-impaired and Native American students to reach mathematics objectives: 4 to 1 (Suppes, Fletcher, and Zanotti, 1975)
- Overall ratio of time needed by individual students to learn in grades K–8: 5 to 1 (Gettinger, 1984)
- Ratio of time needed by undergraduates in a major research university to learn features of the LISt Processor (LISP)[4] programming language: 7 to 1 (Private communication, Corbett, 1998)

As with the differences between one-on-one tutoring and classroom instruction, we may not be surprised to discover differences among students in the speed with which they

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[4] LISP is a language used for artificial intelligence (AI). AI pioneer John McCarthy formulated LISP in the late 1950s.

are prepared to learn. However, the magnitudes of the differences may be much larger than we expect. As we might expect from Gettinger's 1984 review, a typical K–8 classroom will have students who are prepared to learn in one day what it will take other students in the same classroom 5 days to learn. More homogeneous grouping of students based on their abilities does not seem to mitigate this difference. The students in Corbett's 1998 university study are highly selected, averaging well above 1300 on their Standard Acceptance Tests (SATs); however, the differences in time they required to learn the fundamentals of a modestly exotic programming language remain large.

Initially, students' ability may cause the differences in the speed with which they reach given objectives, but prior knowledge quickly overtakes this effect as a determinant of pace (Tobias, 1982). Despite our efforts to sustain common levels of prior knowledge in classrooms by bringing every student to some minimal threshold of learning, we instead appear to increase the differences among students by about 1 year for every year they spend in elementary school (Heuston, 1997). For instance, the average spread of academic achievement in grade three is about 3 years. By grade six, it increases to about 6 years. We are, then, working hard to make the classroom teacher's job more difficult.

The challenge that this diversity presents to classroom teachers is daunting. How can they ensure that every student has enough time to reach given instructional objectives? At the same time, how can they allow students who are ready to surge ahead to do so? The answer, of course, despite heroic efforts to the contrary, is that they cannot. Most classrooms contain many students who at one end of the spectrum are bored and at the other end are overwhelmed and lost.

One-on-one tutoring allows us to alleviate this difficulty by adjusting the pace of instruction to the needs and abilities of individual students. We can proceed as rapidly or as slowly as needed. We can skip what individual students have mastered and concentrate on what they have not mastered.

As with intensity or interactivity, we cannot make a direct cause-and-effect case for the contributions of individualized pace of instruction. However, with pace, as with interactivity, we find that a large difference in instructional treatment is associated with a large difference in instructional outcome. It does not seem unreasonable to conclude that the ability to adjust the pace of instruction may also account for some of the large differences that favor individual tutoring over classroom instruction.

Again, we might ask if CBI, like one-on-one tutoring, allows us to individualize the pace of instruction (with the pace defined by the amount of time it takes students to reach given instructional objectives). Research findings suggest that it does. If students who could move through instructional material more quickly are prevented from doing so in classrooms but are allowed to do so in CBI settings, we should find students reaching instructional objectives more quickly in CBI settings than in classroom settings.

This finding arises repeatedly in reviews of instructional technology. Orlansky and String (1977) found that reductions in time to reach instructional objectives averaged about 54 percent across 12 CBI evaluations used in military training. Fletcher (1991) found an average time reduction of 31 percent in 6 studies of interactive videodisc (IVD) instruction applied in higher education. Kulik (1994) and his colleagues found time reductions of 34 percent in 17 studies of CBI used in higher education and 24 percent in 15 studies of CBI used in adult education. These reviews are effectively independent because they reviewed different sets of evaluation studies. From these reviews, it seems reasonable to expect time reductions of about 30 percent when students use CBI to reach a variety of given instructional objectives.

It is not certain that these reductions result from the speed with which students progress through fixed sets of items, from adjustments in content to take advantage of what students already know or have mastered, or from some combination of these. However, if we simply consider pace to be the rate with which students reach instructional objectives, it seems reasonable to conclude that CBI reduces time to learn, as does one-on-one tutoring, primarily by not holding back students who are ready to progress.

There are three points to add to this discussion:

- First, the self-pacing enabled by technology-based instruction does not simply allow students to skip through content as rapidly as they can. Instead, most and perhaps all technology-based instruction includes an executive agent. This executive agent might be called an instructional management system. It allows students to progress through content as rapidly as possible—but only after they demonstrate their readiness to do so. The instructional management system ensures instructional progress and quality in ways that books, as passive media, cannot.
- Second, reducing instructional time by 30 percent is a fairly conservative target. Commercial enterprises that develop technology-based instruction for the Department of Defense (DoD) regularly base their bids on the expectation that they can reduce instructional time by 50 percent, while holding instructional objectives constant. Noja (1991) has reported technology-based-instruction

time savings as high as 80 percent in training operators and maintenance technicians for the Italian Air Force.

- Third, time saved in learning is not a trivial matter. The Department of Defense spends about $4 billion a year on specialized skill training, which is the post-basic training needed to qualify people for the many technical jobs (e.g., wheeled vehicle mechanics, radar operators and technicians, medical technicians) needed to perform military operations. If DoD could reduce by 30 percent the time to train 20 percent of the people undergoing specialized skill training, it would save over $250 million per year. If it could do so for 60 percent of the people undergoing specialized skill training, it would save over $700 million per year.

Assigning dollar values to the time that students spend in educational settings, especially our K–12 classrooms, is more difficult. This difficulty may account for the paucity of results that can be found for time savings in K–12 education. However, time so spent or saved is not without cost and value. Aside from the obvious motivational issues of keeping students interested and involved in educational material, students who use their time well will profit themselves and any society that depends on their eventual competency and achievement. The time savings that technology-based instruction offers in K–12 education could be more significant and of greater value than the time savings obtained in post-education training.

G. COST EFFECTIVENESS

The issue for any educational decision-maker faced with a unyielding budget, an unpredictable revenue stream, and unending demands for expenditures that are both urgent and imperative is not limited to instructional effectiveness. The core of such decision-making is not just effectiveness but what must be given up to get it. Most often and most specifically, this consideration centers on costs and cost effectiveness.

Is there evidence that technology applications in instruction are cost effective? Despite the decision-makers' uncompromising need for such evidence, little evidence exists to aid their deliberations. This situation is especially prevalent among innovations, such as technology-based instruction, where researchers often seek to learn if an approach "works" or if it works better than existing practice but seldom to determine if it works well enough to justify its expense. The expense issue requires consideration of costs, cost models, and similar issues that researchers in instructional procedures and practices prefer to leave to others. An innovation's cost effectiveness is rarely considered by anyone other than the decision-maker who will be pressured to adopt it.

Of course, asking if an approach is cost effective oversimplifies the issue. Cost effectiveness is a relative term. We cannot meaningfully label some approach as cost effective without specifying the alternatives with which this approach is being compared. Cost-effectiveness studies require the use of a single experimental paradigm—using comprehensive models of costs and effectiveness—to compare the alternatives under consideration. Typically, cost-effectiveness investigators either observe different levels of effectiveness achieved while holding costs constant or they observe the different costs required to reach fixed thresholds of effectiveness.

Such comparisons in technology-based instruction are hard to find—even in industrial training where all decisions are a matter of profit and loss and in military training where allocations of resources may literally be a matter of life and death. Fletcher (1997) reported a limited cost-effectiveness argument for technology-based education. He presented empirical data gathered from earlier studies by Jamison et al. (1976), Levin, Glass, and Meister (1987), and Fletcher, Hawley, and Piele (1990) to compare the costs (adjusted for inflation) of different educational interventions to raise 5th grade mathematics scores on a standard achievement test by one standard deviation. Providing daily 10-minute CBI sessions was found to be less expensive (and, hence, more cost effective) than peer tutoring, professional tutoring, decreasing class size from 35 to either 30 or 20, or increasing the length of the school day by 30 minutes. This finding suggests that a strong cost-effectiveness position for technology-based instruction is likely even at this early (relative to what may be coming) stage of development. Given that we are most likely in the horseless carriage years of the third revolution in learning, these are promising results. More work of this sort is needed.

H. INTELLIGENT TUTORING SYSTEMS

If interactivity and individualization of pace can be achieved by standard approaches to CBI, is there any reason to pursue more exotic approaches? Specifically, is there any reason to develop what are called intelligent tutoring systems (e.g., Woolf and Regian, 2000)?

"Intelligent tutoring systems" may be as intelligently, or unintelligently, designed as any others. They involve a capability that has been developing since the late 1960s (Carbonell, 1970) but has only recently been expanded into general use. In this approach, an attempt is made to mimic directly the one-on-one dialogue that occurs in tutorial interactions. Carbonell was a computer scientist who focused on the underlying computation

capabilities needed to support this approach. He contrasted ad-hoc frame-oriented (AFO) approaches with information structure-oriented (ISO) approaches. Today, we might be more likely to discuss "knowledge representation" as the requisite capability, but, in either case, the software requirement is to represent human knowledge—knowledge of the subject matter, knowledge of the state of the student, and knowledge of teaching strategies.

More important for those who wish to focus on instructional rather than computational capabilities are the functionalities that distinguish intelligent tutoring systems from their predecessors. Despite current marketing efforts to describe any instructional system that uses technology as being an intelligent instructional system, clear differences exist between what has long been the objective of these systems and what has long been available in the state of the art.

Two functionalities are critical and discriminating in an intelligent instructional system:

- First, we expect to find an ability to generate computer presentations and responses in real time, on demand, and as needed or requested by learners.
- Second, we expect to find an ability to support mixed initiative dialogue in which either the computer or the (human) student can generate, ask, and answer open-ended questions.

Notably, instructional designers do not need to anticipate and pre-store these interactions. The motivation for funding the development of intelligent instructional systems in the early 1970s was not to apply artificial intelligence (AI) or ISO techniques to CBI nor was it to mimic one-on-one tutorial dialogue. Instead, it was to reduce the costs of instructional materials' preparation by developing capabilities to generate them on-line, in real time. Generative capabilities were intended to reduce the time and resources needed by the other approaches for anticipating and pre-specifying all possible student-computer interactions.

Currently, intelligent tutoring systems are more sophisticated computationally and functionally than other more typical CBI systems, but they remain expensive to produce. These systems can, of course, adjust the pace, sequence, interactivity, style, difficulty, and so forth of instruction to the needs of individual learners, just as other approaches can. They can also make many of the adjustments to individual learners that human tutors can make. The cost to produce these systems will decrease as our techniques to develop them improve, but they may also be justified by increases in learner achievement. For instance, these systems show an increase in average effect size to 0.84 standard deviations (Fletcher, 1997),

which exceeds the average 0.42 standard deviations (e.g., Kulik, 1994) found for other CBI approaches.

However, the main argument in favor of these intelligent tutoring systems is that they raise the bar for the ultimate effectiveness of technology-based instruction. Their unique generative and mixed initiative capabilities should eventually allow richer, more comprehensive, and more effective interactions to occur between students and the instructional system.

If Kurzweil (1999) is correct, we can expect a $1,000 unit of computing to equal the computational capability of the human brain by the year 2019 and exceed it thereafter. Computers may then become more effective in providing instruction than human tutors even if humans use all the techniques Graesser et al. (1995) found that they now neglect. We may not be implanting integrated circuits in our brains as Kurzweil suggests we might by 2029; however, using computers to discover more than any human agent can about the unique potential of every individual and devising effective and individualized procedures to reach this potential seem to be appealing and realistic prospects.

Whatever the case, the extensive tailoring of instruction to the needs of individual students that can be obtained by using generative, intelligent tutoring systems can only be expected to increase. Our current approaches may be reaching their limits. Intelligent tutoring systems may make available far greater instructional effectiveness and efficiencies than we can obtain from the approaches we are using now.

I. THE COLUMBUS EFFECT IN INSTRUCTIONAL TECHNOLOGY

Prognostications aside, technological approaches to instruction may provide yet another example of what might be called the Columbus Effect. As readers will recall, Columbus sailed west intending to find India (and a lucrative spice route). Instead, he (re-) discovered what became a new world for Europeans. Such a result typifies technological progress. Seeking one thing based on familiar, common practice, we inevitably end up with something else—unforeseen and unexpected. Wireless telegraph produced something functionally quite different from the telegraph—namely, the radio. Similarly, efforts to make a carriage move without a horse produced automobiles, to say nothing of gas stations, motels, and the Santa Monica Freeway. In seeking affordable one-on-one tutoring through automation, we may end up with something no one now envisions. The metaphor based on current practice gets us started. The result may surprise us all.

As we begin with a vision of one-on-one tutoring made affordable through technology, our work may center on efforts to mimic the interactions that occur between human tutors and their students. We may be pursuing human-less tutoring (just as books, television, and other noninteractive media may be viewed human-less lecturing), but we are likely to end up with something quite different in function, appearance, and use.

The advanced distributed learning (ADL) initiative currently being pursued jointly by DoD and the White House Office of Science and Technology Policy (OSTP) gives us a hint of what this different result may be. This vision is based on the expectation that most, if not all, human knowledge will become available as shareable, interoperable objects on the World Wide Web. The ADL initiative seeks to specify and develop these objects, but it does so because it envisions something that might be called a personal learning associate (PLA).

Physically, a PLA will be a computer that is either carried or worn. In keeping with the suggestions of Kurzweil and others, it may even be implanted to provide direct brain-computer interaction, although this possibility seems more distant and needs more review and consideration. Functionally, a PLA will provide wireless connection to the Web or its successor in the global communication arena. A student of any age will use it for learning, and decision-makers (e.g., electronics technician, military tactician, or business planner) will use it to help solve practical problems.

All users will interact with the PLA through spoken, natural language. It will provide a full range of display capabilities, including text, graphics, and photographs, as specified by the apocryphal Committee's specifications. It will also provide animation, digital video of some sort augmented by a full range of high-fidelity sound, and, perhaps, tactile and haptic feedback. Olfaction remains under review.

Most of the PLA's physical capabilities are state of the art. Many of the software capabilities are also available or, like shareable courseware objects, soon will be (Fletcher and Dodds, 2000). Its instructional and decision-aiding functionalities remain longer term and more elusive. These functionalities call for the PLA to develop and then use comprehensive, intimate, and accurate knowledge of the student/user to identify, collect, and integrate shareable instructional objects. This process will be accomplished on demand and in real time and will be precisely tailored to the individual's needs, capabilities, interests, and cognitive style. If the intention is to help solve a problem, information that the PLA provides will not just be expert, but will also be delivered in a form that the individual can understand. If the intention is to establish a more permanent change in the individual's cognitive ability

(i.e., to bring about learning), the PLA will do so efficiently and effectively in ways far superior to those that we now imagine.

Obviously, we have a way to go to realize this vision. What form it eventually takes, how it is used, what infrastructure it engenders, and what impact it has on our lives remain to be seen, but its key capabilities may arise from the intelligent instructional systems we are now learning to build. The Columbus Effect will kick in sooner or later, but beginning with a guiding metaphor based on individualized, tutorial instruction and "mentoring" seems a good way to advance. The goal of learning to do something that is within our reach but outside our grasp has long been a stimulus for human progress.

J. IMPACT ON RESEARCH AND THEORY

Reviews by Krendl and Lieberman (1988) and Schater and Fagnano (1999) continue to echo earlier recommendations by Suppes (1964) and others to apply advances in cognitive and learning theory to the development of technology-based instruction. Such efforts will improve the quality of instruction delivered. More importantly, these efforts will provide feedback to theories of cognition and learning to indicate where they are right, where they might use some improvement, and where they have left serious gaps that need to be filled. This is the traditional interplay of theory and empirical research that has served other areas of systematic investigation so well. Technology-based instruction, with its precise control over stimulus inputs and equally precise measurement of response outputs, should play a unique role in completing the feedback loop between theory and empirical research.

Such feedback will produce significant advances not just in instruction, but also in related areas. Instructional applications that use technology test the notions—or theories—of human cognition, learning, and instruction embodied in them in at least two ways:

- First, the ability to put a proposed notion, model, or theory into a computer algorithm is a significant demonstration. If a notion cannot be captured by an algorithm, it may not be testable. If it is not testable, it is not worth serious consideration.
- Second, an instructional application is an instantiation that tests the correctness of a notion, model, or theory. To the extent that an application achieves its goals, the notion(s), model(s), or theory of cognition, learning, and instruction on which it is based can be viewed as correct. However, tests of instructional applications seldom yield simple answers. The fine-grain data that technology-based instruction makes available will increase the richness of the feedback

we receive. Few theories will be shown to be perfectly and thoroughly correct. The more complete diagnostic information concerning where they are correct, where they are not correct, and what they lack is critical. Detailed and specific information of this sort produces significant advances in other fields, and we should expect nothing less from our instructional applications.

K. THE ENGINEERING OF INSTRUCTION

Beyond issues of feedback for theory, our third revolution in learning may effect a shift in instruction from art to engineering. We tend to view teaching as an intensely "human" activity, something that at best can only be accomplished by human teachers interacting with human students. Master teachers do exist, and many of us have benefited from the attentions of at least one teacher who, if not a master, was at least able to impress on us the value, benefits, and pleasure of scholarship. However, such occasions appear to be more the exception than the rule. Our perceptions of teaching as a warmly experienced, human activity vary with much that we experience in real classrooms, where each student is one of many waiting for that portion of instruction that addresses his or her individual needs.

To a great extent, successful instruction is a matter of design—the creation of an environment to maximize the probability that learning will occur and that every student will achieve specified instructional objectives. Mostly, we seek and test for accuracy of knowledge. However, we may also seek other objectives such as speed of response, retention, insight, and transfer of knowledge as well as continued interest in and respect for the subject matter. These goals may be compatible to some extent, but, at some point, they diverge and require different approaches that compete with each other for classroom resources of human energy, funding, and, especially, time.

The design of such an environment may be viewed as an art—a highly personal, hit or miss affair. To be fair to our students and productive in our instruction, we need to establish a science of design that allows these many instructional objectives to be accomplished by many different hands. In short, we need an engineering of instruction in which specific designs reliably yield specific instructional outcomes.

The notion of instruction as engineering may be unpopular. Raymond Fox (1994) has noted that "one of the more difficult problems in dealing with improvement in public education is to replace the notion of teaching as an art form with that of instruction delivery as a systems science" (p. 2). Without technology, precise engineering to ensure that every student achieves a wide range of objectives would be out of the question. Different human

teachers, specifically because they are human, must approach their students differently and succeed in different ways with different students. One-on-one tutoring can accomplish this goal to some degree, but the precision, "patience," and consistency of technology may surpass what we can accomplish with human tutorials. A technology-based approach may provide the individual, precisely tailored attention that each student needs to achieve fully his or her potential.

L. IMPACT ON OUR CURRICULAR GOALS

In 1960, T.F. Gilbert wrote:

> If you don't have a gadget called a "teaching machine," don't get one. Don't buy one; don't borrow one; don't steal one. If you have such a gadget, get rid of it. Don't give it away, for someone else might use it. This is the most practical rule, based on empirical facts from considerable observation. *If you begin with a device of any kind, you will try to develop the teaching program to fit that device* [p.478 (the italics are Gilbert's)].

Gilbert may be right and wrong. He is certainly correct in suggesting that instructional designers and developers who use a "teaching machine" will try to fit the teaching program to it. The new functionalities that such a device makes available motivate its use in the first place. One can imagine students long ago poring over clay tablets or papyrus rolls once their teachers learned how to design teaching programs to take advantage of written language. The same can be said for printed books, which, because they were more accessible and less expensive than papyrus rolls or codices, allowed teachers different assumptions in the development of their teaching programs. The same is doubtlessly true for our third instructional revolution, which applies interactive, computer-based technology to the problems and processes of instruction.

It is less certain whether such adaptations (e.g., fitting the teaching program to the "device") are significant evils to be avoided at all costs. Certainly, if technology causes us to remove or de-emphasize essential elements of our teaching programs, it will diminish their effectiveness. However, if technology is properly applied, it will improve, if not revolutionize, the effectiveness and efficiency of our teaching programs. Researchers, developers, and instructors—not the technology itself—must ensure that it does.

In either case, the application of technology will change what and how we teach. Technology will raise the bar for our curricular aspirations. Tutorial simulations will afford our students experiences, access to exotic (i.e., expensive and unavailable) devices, and immersion in collaborative problem solving that we could not provide in any other way.

Intelligent tutoring capabilities will permit tutorial interactions or simple conversations with experts and expertise that would otherwise be out of the question. Because these interactions will be geared to each student's level of ability and prior knowledge, they will produce levels of understanding that would otherwise be unattainable. Sooner or later, we will be forced by necessity, public pressure, or our own professional integrity to adapt our teaching programs to the new functionalities that technology makes available. The most important consequence of the third revolution in instruction may not be that it improves efficiency and effectiveness of what we do now, but that it changes what it is that we choose to do.

M. SUMMARY

More discussion needs to take place about the third revolution in learning wrought by technology, but that discussion must await wiser, better-informed commentary. However, with modest certainty, a few statements can be made. This revolution will:

- Make the functionalities of individualized tutoring widely accessible and affordable
- Permit interactive, individualized learning to take place anytime, anywhere
- (Eventually) bring about profound changes in our educational institutions and the roles and responsibilities of people (teachers, students, and administrators) in these institutions
- Help bring into being a nation of life-long learners who are well prepared to meet the challenges of the new century and thrive in the global marketplace
- Lead to capabilities, uses, and functionalities of which we are now only dimly, if at all, aware (thanks to the Columbus effect)
- Produce radical change in the practice and processes of instruction.

Basically, people learn just one way, and this way mostly likely requires growth or chemical changes in the synapses. The third revolution in learning will not change learning at this level any more than writing or books did. However, substantially increasing the probability that such fundamental changes will occur across all manner of humans in all manner of environments does seem to qualify as a radical change—one that warrants the term "revolution." Because this revolution will increase the tempo with which learning occurs, it might be called a revolution in learning, the magnitude of which we have only seen twice before in human history.

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GLOSSARY

ADL	advanced distributed learning
AFO	ad-hoc frame-oriented
AI	artificial intelligence
AL	Armstrong Laboratory
CAI	computer-assisted instruction
CBI	computer-based instruction
DoD	Department of Defense
DTIC	Defense Technical Information Center
HR	Human Resources
IDA	Institute for Defense Analyses
IVD	interactive videodisc
IEEE	Institute of Electrical and Electronics Engineers
ISO	information structure-oriented
ITS	intelligent tutoring system
LISt	LISt Processor (a programming language)
MIT	Massachusetts Institute of Technology
OJT	on-the-job training
OSTP	Office and Science and Technology Policy
PLA	personal learning associate
SAT	Standard Acceptance Test
TP	Technical Project

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14. ABSTRACT

Writing and printed books have influenced learning profoundly. It seems reasonable to view the emergence of writing as the first major revolution in learning. By making the content of learning, teaching, and educational material widely and inexpensively available anytime and anywhere, the development of books printed from movable type effected a second revolution in learning. Can we improve on books? Computer technology is a possibility because computers can adapt the content, sequence, type, difficulty, granularity, and so forth of their presentations to learners or problem solvers based on ongoing, dynamic assessments of individual needs. For this reason, computer technology may be effecting a third revolution in learning. While preserving the capabilities of books to present the content of instruction anytime, anywhere, computers can also provide the interactions of teachers, instructors, tutors, and mentors as needed by individual learners and users. This capability may produce a third revolution in learning, with a significance equal to that of the development of writing and books. This document addresses this "Third Revolution" in learning by assessing the impact of computer-based technology on learning. Consequences of this third revolution include making individualized tutoring widely accessible and affordable; permitting interactive, individualized learning to take place anytime, anywhere; changing the way that educational institutions and educators view learning by producing radical changes in the practice and processes of instruction; and bringing into being a nation of life-long learners who are prepared to meet future technological challenges and thrive in the global marketplace.

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